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AN ANALYTICAL STUDY OF LOW CYCLE FATIGUE EFFECTS IN BUCKLING RESTRAINED BRACES

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Abstract. *Dampers are used in structures to dissipate input energy caused by severe earthquakes. They can also reduce seismic demands on other structural elements. So dampers' life is a significant parameter to prevent the structural damages. One of the failure modes observed in the steel dampers during earthquakes, is the damage caused by cumulative effects due to few cycles of high strain amplitudes. This undesirable effect is called Low-Cycle Fatigue (LCF). In buckling restrained braced frames (BRBFs), brace element acts as a hysteretic damper and dissipates high amount of input energy by plastic axial deformations. To ensure satisfactory operation of BRB with no failure during earthquake, it is necessary to investigate LCF effects. On the other hand smaller yielding length of BRB cores imposes higher strain amplitudes and makes the LCF failure more probable.*

In the present study, a criterion to control LCF failure in BRB has been selected based on fatigue life equations recommended in the previous experimental researches. A 7 story benchmark building with BRBs as the lateral resisting system is selected. Then the yielding length of BRB has been reduced to the minimum possible based on the fatigue criterion and the building has been redesigned. Fatigue analysis has been performed on both buildings to evaluate LCF capacity. In order to evaluate fatigue effects, time history analysis have been conducted on both buildings using the open source finite element platform, OpenSees (2005). Strain history demands in each yielding segments of the braces have been extracted and the cumulative damage index of Palmgren-Miner has been calculated to estimate LCF damage index.

Results of this study show that despite the high cumulative plastic deformations the yielding segments experiences, both BRBs have proper fatigue damage indeces. Also it has been proved that developed criterion for controlling LCF failure is conservative for selected time histories and has appropriate safety factor for defining reduced core length of BRB.

1 INTRODUCTION

Braces are usually designed to act as energy dissipating members in seismic design of concentrically bracing systems. Therefore a brace is anticipated to have a stable cyclic behavior with high damping hysteresis loops. Due to buckling, the majority of the energy that could be damped in compression is lost and the brace stability is jeopardized. In Buckling Restrained Braces (BRBs), by preventing the buckling of the brace, a symmetric and stable hysteresis curve is achieved that dissipates high amount of energy in every single cycle (figure 1).

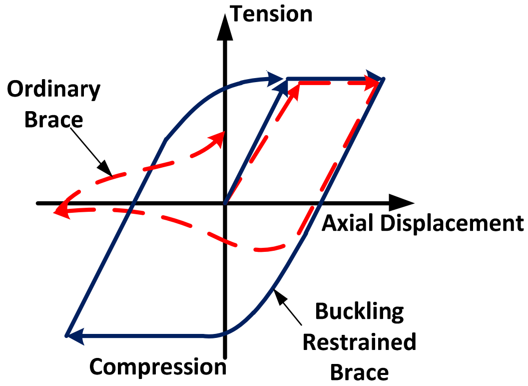

Figure 1: Cyclic behaviour of a typical BRB versus a conventional brace [1].

BRBs brilliantly solve problems of classic concentric braces, which are characterized by a pinched hysteresis loop and a small ductility due to the concentration of strain occurring when braces buckle [2]. In common BRBs, the axial deformation is distributed in a large length, so the peak strain amplitude typically falls in the range of 0.01–0.02 for usual structural applications [3]. On the other hand, the results of experimental studies on BRBs proved the capacity of core to endure the strains of higher ranges up to 0.03 or even 0.06 [3, 4]. The capacity of withstanding high strains insures the feasibility of reducing the length of the yielding segment of BRBs. Reducing the length of yielding segment in BRBs has a number of advantages. By reducing the yielding segment higher axial stiffness in brace is achieved. On the other hand, the restrained length is reduced so global encasing member can be replaced by a local one that has less weight and cost. Yielding part of BRB is the structural fuse in BRBFs and its length reduction causes a more flexible designing since in small sizes a variety of core lengths and cross sectional areas can be provided. If a fuse replacement is needed after sever earthquakes, it is enough to replace damaged fuse with a new one (only at the end of the brace) and it is not necessary to replace the whole brace [1].

The above advantages raised the interest of many researchers to investigate the possibility of reducing core length in BRBs. The majority of these studies have been carried out in recent 5 years. Table 1 summarizes some of these studies.

Researcher	Year	Location	L_c/L	Model	Max Strain
Tremblay et al.	2006	Canada	25%	Experimental & Analytical	3.4%
Mirghaderi & Ahlehagh	2008	Iran	35%	Analytical	4.3%
Ning Ma et al.	2009	China	20%	Experimental	3.4%
Mazzolani et al	2009	Italy	40%	Experimental	3.5%
Razavi & Mirghaderi	2009	Iran	20-40%	Analytical and Experimental	3-4%
Di Sarno & Manfredi	2010	Italy	20%	Analytical	1.5%

Table 1: Summary of some studies on BRB with reduced core length [3-7].

Nevertheless, reducing the yielding length imposes large strain demands on this segment which poses some concerns about Low-Cycle Fatigue (LCF) failure. However, a minimum core length is required to keep inelastic strain demand low enough such that LCF fracture of the core does not occur under a severe earthquake [3].

Since various ranges of BRB core length can be used, it is necessary to consider the effects of LCF on BRBs. Unfortunately seismic codes and specifications have not presented any distinct criterion to control these effects. So, in recent years, a series of experimental studies was accomplished on the possibility of fracture of BRBs caused by LCF. Moreover, some qualification tests with respect to LCF effects have been developed.

In the present study a series of LCF tests on BRBs are mentioned. Based on the tests results, an index to estimate fatigue life of BRBs is selected. Using this index, a criterion is presented to determine the minimum needed yielding length to prevent LCF failures. The next step is to redesign a benchmark 7 story BRBF utilizing BRBs with minimum yielding length. Time history analyses were conducted on the two buildings using the open source finite element platform, OpenSees (2005). Based on the results, an index of LCF damage is calculated for each brace to evaluate the accuracy of the presented criterion. To compare ductility demands on the primary and secondary frames, the maximum and the cumulative ductility in yielding length of BRBs were calculated.

2 LOW CYCLE FATIGUE

Common plasticity models used in civil engineering normally predict the nonlinear behavior of metallic elements under cyclic loading and commonly do not address the fatigue failure. The issue of LCF is not explicitly mentioned in seismic design standards such as Seismic Provisions for Structural Steel Buildings (AISC/ANSI 341-05) [8] and Seismic Rehabilitation of Existing Buildings (ASCE/SEI 41-06) [9]. However one of the most important issues in cyclic behavior of the metallic dampers can be the failure caused by repetitive large inelastic strains. This phenomenon is called LCF and usually occurs in members under severe cyclic loadings such as earthquake loading.

BRB dissipate energy by formation of plasticity in their core segment. As the strain amplitudes in normal BRBs are minimal, no many researches have been conducted on the LCF of normal BRBs. However when the length of the core segment is reduced the strain amplitudes rise and LCF failure could be a concern. Evaluating LCF effects requires enough data about the LCF capacity based on tests and selecting a damage evaluation process.

2.1 Low-Cycle Fatigue Capacity of BRBs

The capacity of metallic material against LCF is commonly expressed by Coffin-Manson equation [10].

$$\frac{\Delta\varepsilon_p}{2} = \varepsilon'(2N)^C \tag{1}$$

where:

- $\Delta\varepsilon_p/2$ is the plastic strain amplitude
- ε_f' is fatigue ductility coefficient
- 2N is the number of reversals to failure (N cycles)
- c is the fatigue ductility exponent

This equation is usually used to estimate the fatigue life of a specimen under constant plastic strain amplitudes. The parameters of this equation are extracted from tests. Material tests are typically conducted on small specimens which greatly differs from BRB specimens. LCF life has found to depend on many factors such as specimen shape and size, and stress concentrations [10]. Thus individual tests on steel material in BRB scale is needed to evaluate the LCF capacity of a BRB. Many researchers have attempted to investigate LCF effects in steel material or members and present a Coffin-Manson type equation to predict the fatigue life (N_f). A number of these studies will be presented.

In 2000 Nakamura et al tested five BRBs on behalf of Nippon Steel. This research intended to clarify hysteresis stability and fatigue failure characteristics of the braces by performing fatigue tests on practical scale unbounded braces [11]. Based on the test results of BRBs with different core steel grades including JIS SN400B, and LYPI00 and LYP235 a relationship between applied strain and fatigue life was presented:

$$\Delta\varepsilon_c = 0.2048(N_f)^{-0.49} \tag{2}$$

Where $\Delta\varepsilon_c$ is the strain amplitude of the core.

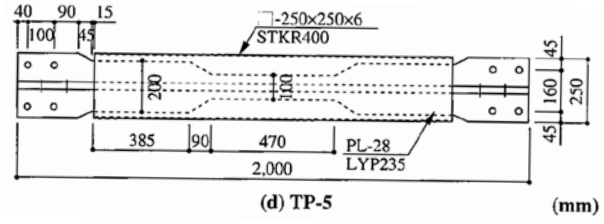

Figure 2: TP-5 specimen detail [11].

Most of failures occurred near the welding areas or reinforcing ribs that indicates stress concentration greatly decreases the fatigue properties of a BRB. The test results showed that the values of the failure cycle number (N_f) in the core model tests were 1/2 to 1/5 of those in the material tests, and those in the practical-scale tests were 1/6 to 1/10, presumably because of influences of stress concentration at the ends of the reinforcing ribs or that caused by local buckling. LYP100 and SN400B showed nearly identical plastic fatigue characteristics.

In 2002 S. L. Lin and Keh-Chyuan Tsai conducted performance tests on an all metallic detachable buckling restrained braces some of which included fatigue tests [12]. Various strain amplitudes were experimented and based on the results the following fatigue life equation was presented:

$$N = 0.0007(\varepsilon_c)^{-2.25} \tag{3}$$

Where N is the maximum tolerable cycles in strain of ε_c that occurs in BRB core.

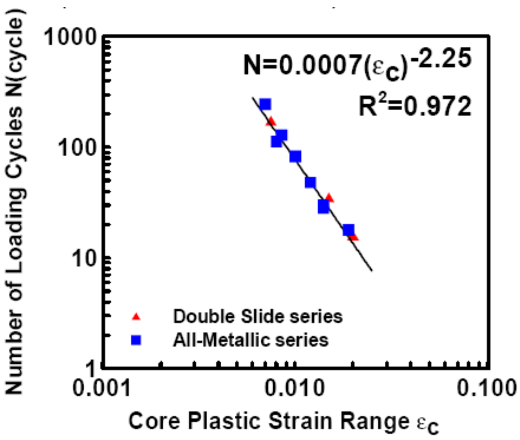

Figure 3: Number of fatigue strain cycles versus core strain relationship [13].

Other researchers have evaluated the fatigue properties of different type of BRBs. Table 2 shows a summary of the BRB fatigue studies which have presented a Coffin-Manson type equations.

Researcher	Year	Location	Equation	Material	Test Type
Nakamura et al	2000	Japan	$\Delta\varepsilon_c = 0.2048(N_f)^{-0.49}$	SN400B LYP100 LYP235	Uniaxial
Isoda et al	2002	Japan	$\Delta\varepsilon_c = 0.20(N_f)^{-0.39}$	LY225	Uniaxial
Nariharah (22278)	2002	Japan	$\Delta\varepsilon_p = 0.3770(N_f)^{-0.602}$	SN400B	Sub-assemblage
Horie et al	2003	Japan	$\Delta\varepsilon_c = 0.2(N_f)^{-0.41}$	SNB400	Uniaxial
Tsai	2003	Taiwan	$N_f = 0.0007(\varepsilon_c)^{-2.25}$	A572 GR50	Frame
Kamura et al	2009	Japan	$\Delta\varepsilon_t = 0.1128\ (N_f)^{-0.4129}$	LY100	Uniaxial

Table 2: Fatigue life prediction equations [11, 13-17].

The fatigue behavior of BRBs has been studied in other researches too. In these researches usually some extra load cycles have been exerted on the specimen after the specimen has withstood the total loading protocol for qualification test according to relevant code [18-20].

Some other researchers have reported the cumulative inelastic axial ductility capacity (η) and have compared it to 200 which is noted in AISC 341-05 as a satisfactory fatigue property. It seems evaluating LCF failure only based on the cumulative inelastic axial ductility cannot consider the LCF effects completely, since strain amplitudes are of great importance in LCF failure.

From the LCF experimental studies of BRBsthe following conclusions can be derived:

- LCF capacity depends on various factors such as: the shape of core segment, the stiffness of buckling restraining mechanism, the width-thickness ratio of the axial member, clearance between the axial member and the restraining mechanism, eccentricity in the core segment, overall detailing of the BRB, the quality of manufacturing.
- Presence of any discontinuities, tack welds, attachments in core segment which is identified as protected zone per AISC 341-05 severely degrades the LCF life.

- LCF failure occurs soon after the formation of local buckling in the core segment.
- The local buckling of the core is more probable to happen at the ends of core segment [3, 21].
- Using flat plates in core segment show better fatigue properties in comparison to cruciform sections [11].
- The strain rate has minimal effect on hysteretic behavior, cyclic stress, and fatigue life for the steel plate especially when the core can dissipate heat through connections or proximity to elastic members [22].
- The overall fatigue life is somehow similar for different steel grades.

In this study the equation for fatigue life prediction presented by Nippon is adopted. Nevertheless the LCF capacity can be greatly increased if enough attention is paid to the results noted above. Though this equation is extracted for specific BRB with a special detailing, but it has been adopted for this study since it holds rational conservativeness.

2.2 Low-Cycle Fatigue Damage Evaluation

Evaluating the damage resulted from repeated cyclic loads commonly follows the Palmgren-Miner rule [23]. According to this theory the damage caused by a strain cycle is defined by the following equation:

$$D = \frac{1}{N_f} \tag{4}$$

So damage caused by “n” strain cycles is equal to:

$$nD = \frac{n}{N_f} \tag{5}$$

In order to calculate the damage index in case of several strain series with different amplitudes the, damage caused by n_i cycles at the strain of ε_{ai} is $n_i D_i = n_i / N_{fi}$. Then the overall damage of the member is equal to the summation of calculated damages [10].

$$\sum \frac{n_i}{N_{fi}} = \frac{n_1}{N_{f1}} + \frac{n_2}{N_{f2}} + \ldots + \frac{n_i}{N_{fi}} \tag{6}$$

Failure is probable when this summation becomes greater than 1.

When a brace is evaluated under a time history, the number of different strain amplitude is not distinctly recognized. In such cases the Rain Flow Counting Method can be applied. Rain Flow counting method is a process to calculate equivalent constant amplitude cycles for a strain or stress time history. This method has been successful [24] and is frequently used in fatigue analysis of seismic resistant systems [25, 26].

In this study the combination of Rain Flow Counting method and the Palmgren-Miner cumulative rule is applied to determine the damage index of the braces in the time history analyses.

2.3 The criterion to determine the yielding length in design procedure of the reduced core BRB

Based on the results of LCF studies, fatigue life of an element under high strain demands depends on the strain history it experiences rather than the maximum amplitude of strain. So at the first step the applicable displacement loading history on the specimen should be determined for designing purposes.

AISC 341-05 [8] suggests a loading protocol for qualification test of BRBs. When these provisions suggested, BRBs with reduced core length were not widely in use. The strain amplitudes in common BRBs are limited to 1% or 2%. Therefore seemingly the suggested protocol has not included the LCF effects. In absence of a specific criterion to control LCF failure, some researchers considered the cumulative inelastic axial deformation of the brace [4]. If the value from BRB test was much greater than 200 (AISC recommended value), they concluded that LCF failure is not probable.

In 2006 another loading protocol was presented by Tremblay et al [3] for testing series of all-steel BRBs some of which had reduced yielding length.

According to provisions of ASCE 41-06 [27], each energy dissipation device shall be loaded with 20 fully reversed cycles at the displacement in the energy dissipation device corresponding to the BSE-2 which represents an earthquake with 2% probability of exceedance in 50 years.

The provision of ASCE 41-06 which defines 20 cycles is based on the earthquake duration of the earthquake not its severity. On the other hand, the provisions of common seismic design codes are usually for design earthquakes corresponding to the BSE-1 which represents an earthquake with 10% probability of exceedance in 50 years. So in order to make the design assumptions of BRB compatible with common seismic systems, the provision of ASCE41-06 can be considered in BSE-1 instead of BSE-2. Table 3 shows loading protocols recommended by various references.

	Recommended Loading Protocol				
AISC	$2\times\Delta_{by}$	$2\times0.5\Delta_{bm}$	$2\times\Delta_{bm}$	$2\times1.5\Delta_{bm}$	$2\times2\Delta_{bm}$
Tremblay	$6\times\Delta_{by}$	$4\times0.5\Delta_{bm}$	$4\times\Delta_{bm}$	$2\times1.5\Delta_{bm}$	$4\times\Delta_{bm}$
ASCE 41-06	-	-	$20\times\Delta_{bm}$	-	-

Table 3: Comparison of loading protocols for BRB tests recommended by different references.

Δ_{by} is the projection of the story drift corresponding to the yielding of the brace on the brace direction and Δ_{bm} is the projection of design story drift on the brace direction.

As mentioned previously, the overall damage of a member is equal to the summation of calculated damages of different cycles. So the damage during the loading protocol should be calculated cumulatively. For this purpose, for each loading protocol the Palmgren-Miner equation is calculated and the result is controlled to be less than one.

3 DESIGNING AND MODELING OF A BRBF BUILDING USING REDUCED CORE BRB AND

The LCF failure is most probable in BRB with reduced yielding length, as the strain amplitudes increase. BRB with reduced yielding segment has two main parts: a short part and a long part. The short part is the restrained yielding part that yields in both tension and compression like a short BRB. This part acts as a structural fuse and is the displacement controlled (D.C.) component of the brace. The long part is the unrestrained non-yielding part without yielding or buckling. This part is expected to be elastic and is the force controlled (F.C.) component [28]. Figure 4 shows the schematic model of the Reduced Length BRB (RL-BRB), where P_y is yielding load of the brace, ε_c is maximum strain of the core, P_{cr} is critical buckling load of the whole BRB and FS is factor of safety.

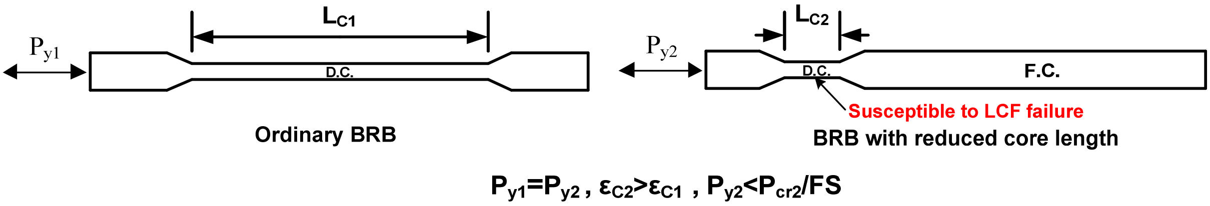

Figure 4: Schematic model of the recommended brace versus schematic model of a conventional BRB [29].

Reducing the yielding part of the BRB will affect the overall behavior of BRBF and also will make the LCF damage more possible since the core strain amplitudes will increase [30]. So the LCF property of frame with RL-BRB is investigated via nonlinear analyses. For this purpose a benchmark BRBF building was redesigned using RL-BRBs. The step by step design procedure for RL-BRBFs was completely discussed in another study by Razavi et al [28].

The original building had been selected from a Steel Tips report entitled as "Seismic Design of Buckling Restrained Braced Frames" [31]. The building is a 7 story BRBF with official application. Four sets of diagonal bracing (BF-1) in X direction and two sets of chevron bracing (BF-2) in Y direction is applied as the lateral resisting frames for a rectangular plan of 40m×25m. The total length of BF-1 braces is 7.5m in the first story and 7m in other stories. For BF-2 braces the lengths are 6.25m and 5.75m respectively. Figure5 shows the geometry of bracing bays. ASCE 7-02 [32] specifications had been used for the loading and the design procedure was originally performed according to FEMA 450 section 8.6 [33].

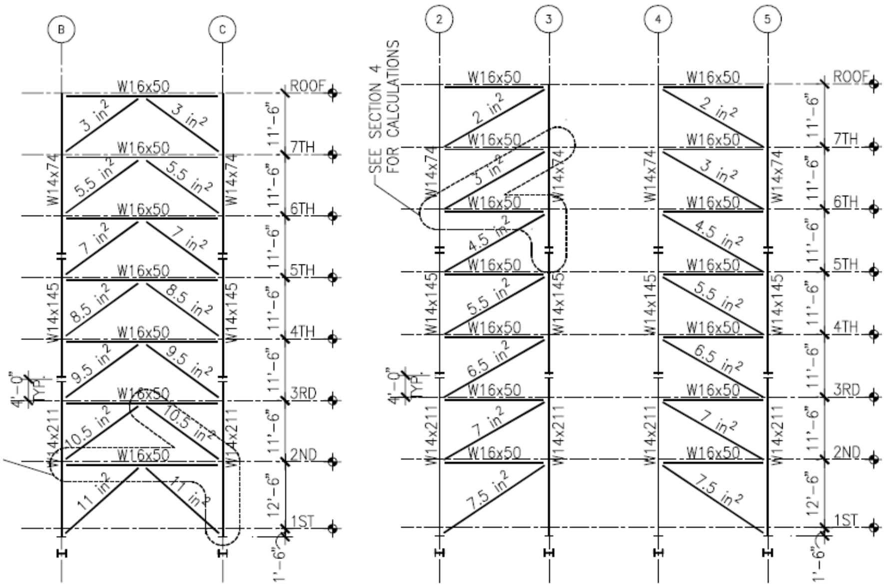

Figure 5: The elevation view of BRBF building. BF-1(left) and BF-2(right) [31].

As this study intends to study the LCF effects of the RL-BRB, the minimum length required is calculated according to the assumptions of previous sections.

In previous sections recommended equations to calculate fatigue life (N_f) of BRBs were presented. N_f can be extracted for every BRB detailing by conducting special fatigue tests. ATC 24 recommends a testing protocol for extracting the parameters in fatigue life estimation equation for steel structural elements. [34]

Tables 4 and 5 show calculated yielding lengths using different loading protocols and different N_f by applying Palmgren-Miner rule for the brace in 5th story and 4th and 5th story of BF-1 and BF-2 respectively. The lengths in the tables are calculated so that the LCF index equals 1. This means no safety factor is adopted in this stage.

	AISC	Tremblay	ASCE 41-06 (BSE-1)
Nippon	130	124	150
Isoda	115	100	171
Narihara	87	89	170

Table 4: Different yielding lengths calculated for BF-1 (cm).

	AISC	Tremblay	ASCE 41-06 (BSE-1)
Nippon	93	88	105
Isoda	81	71	122
Narihara	62	63	121

Table 5: Different yielding lengths calculated for BF-2 (cm).

Table 4 and 5 show that that different loading protocols lead to almost the same results. Using ASCE 41-06 leads in slightly longer yielding segment. In this study, yielding length calculated from the combination of AISC loading protocol and N_f from Nakamura study is selected.

Based on the selected reduced length the building with RL-BRB was analyzed and designed. Comparison of the design results showed that replacing common BRB with RL-BRB does not make a significant change in beams and columns designing. The same cross sectional area of the BRB core also obtained. The comprehensive comparison of design results is discussed by Shemshadian [30].

4 NONLINEAR DYNAMIC ANALYSES OF FRAME WITH RL-BRB

In order to investigate the LCF effects in BRBs of original and redesigned buildings, 28 nonlinear dynamic analyses (Time History Analyses) were conducted on 4 BRBFs. A set of 7 different records were used to consider the average results. These records were selected from PEER database. It was tried to select records with various frequency contents and durations in order to estimate ductility and LCF damage index more accurately. These records are introduced in table 6.

No.	Name	Year	Magnitude	Duration(sec)	Dist. (km)	PGA (g)	PGV (cm/s)	PGD (cm)
1	Duzce	1999	7.1	56	17.6	0.203	17.3	14.29
2	Imperial Valley	1979	6.5	100	43.6	0.145	14.8	8.62
3	Kobe	1995	6.9	41	15.5	0.059	6.4	2.16
4	Kocaeli	1999	7.4	30	17	0.086	8.6	5.52
5	Landers	1992	7.3	28	21.2	0.174	9.9	4.01
6	Northridge	1994	6.7	30	19.6	0.326	16.9	2.56
7	San Fernando	1971	6.6	28	21.2	0.136	4.3	1.52

Table 6: Characteristics of selected ground motions.

Since site parameters in Steel Tips report was given according to ASCE 7-02 [27], the design spectrum of this code was used for record scaling.

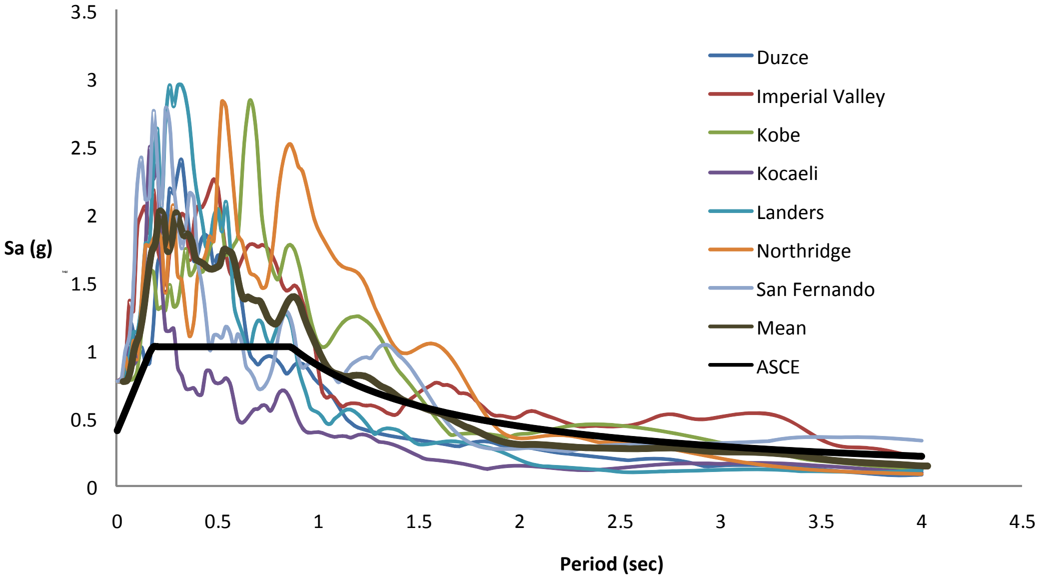

Figure 6: Response spectrum of the selected records with mean and ASCE spectrums.

The results of nonlinear time history analyses show that the maximum and residual drifts of the RL-BRBF are less than the original frame. This is the result of using RL-BRBs instead of common BRBs since RL-BRBs are stiffer [1]. On the other hand the pattern of interstory drifts is almost unchanged that indicates that replacing common BRBs with RL-BRBs does not influence the general behavior of the structure.

5 LOW CYCLE FATIGUE EFFECTS IN YIELDING LENGTH OF BRBS

The strain history of each yielding segment of BRB under each record is extracted. Then the Rain Flow Counting Method is used to calculate the equivalent strain history with complete cycles.

According to the definition of AISC 341-05, cumulative inelastic ductility under a loading is the summation of plastic ductility occurred in the member divided to deformation at beginning of yielding. The loading sequence requires each tested brace to achieve ductilities corresponding to a cumulative inelastic axial ductility capacity of 200 per AISC 341-05 specifications, [8]. Table 7 presents the cumulative inelastic ductilities for strain history of

RL-BRBs yielding length. The values justified that the yielding length of RL-BRBs will undergo large inelastic deformations under selected earthquakes .

Story	**Reduce Length**	
	BF-1	BF-2
7	193	241
6	321	351
5	303	363
4	294	360
3	337	349
2	368	262
1	187	209
Average	286	321

Table 7: Cumulative inelastic ductility in yielding length of RL-BRBs.

In order to control the LCF failure in a reduced yielding segment, LCF damage index should be calculated for equivalent strain history based on the Palmgren-Miner rule. Table 8 shows the results for RL-BRBFs considering Nakamura et al fatigue life equation. Since the tension and the compression braces behaved similarly, a single damage index was presented for every story.

Story	**Reduce Length**	
	BF-1	BF-2
7	0.05	0.07
6	0.12	0.14
5	0.12	0.16
4	0.12	0.15
3	0.14	0.13
2	0.13	0.07
1	0.05	0.06
Average	0.10	0.12

Table 8: LCF damage index for RL-BRBs.

The results confirm that LCF criterion used in design procedure of RL-BRB has an acceptable safety factor (about 6), so LCF failure does not occur under selected records. On the other hand, low damage indices show that ductility demands resulted from loading protocols in design procedure of the yielding length are much higher than ductility demands from analysis.

As an example as noted in table 9 the damage index for the brace in fifth story of RL-BRBF is 0.97. The majority of this (about 88%) is due to strain amplitudes of $1.5\Delta_{bm}$ and $2\Delta_{bm}$. It can be concluded that LCF damage is the result of multiple cycles in great amplitudes.

AISC Protocol	$2\times2\Delta_{bm}$	$2\times1.5\Delta_{bm}$	$2\times\Delta_{bm}$	$2\times0.5\Delta_{bm}$
Strain in yielding segment	5.4	4.1	2.7	1.4
Palmgren-Miner fatigue index in each cycle	0.53	0.30	0.11	0.03
Palmgren-Miner fatigue in the whole protocol	0.97			

Table 9: Palmgren-Miner damage index for the brace of fifth story in RL-BRBF.

On the other hand, based on nonlinear dynamic analyses the mean calculated damage index for this brace is 0.12. For more investigation, the strain histories of this brace under Imperial Valley and Northridge records are considered (Figure 7, 8). These two records have the maximum damage indices.

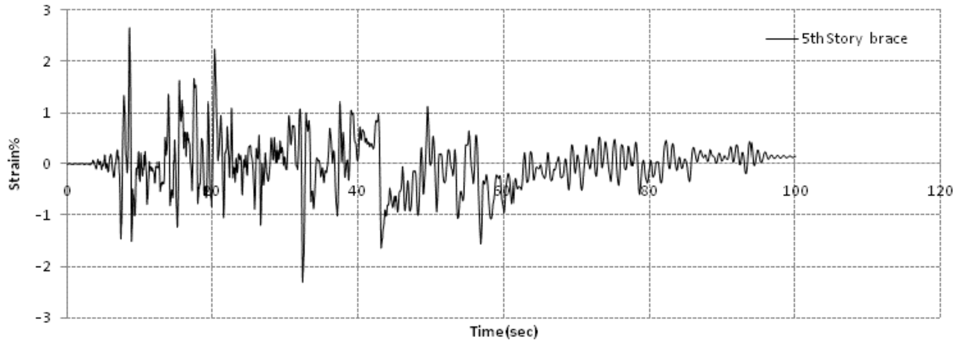

Figure 7: Strain history of fifth story brace in RL-BRBF under Imperial Valley record.

The strain history of Imperial Valley shows that the majority of strain amplitudes are less than 1% and rarely reach 2%. In other words, although the number of cycles is high (the duration of earthquake is 100 seconds) but the strain amplitudes are small.

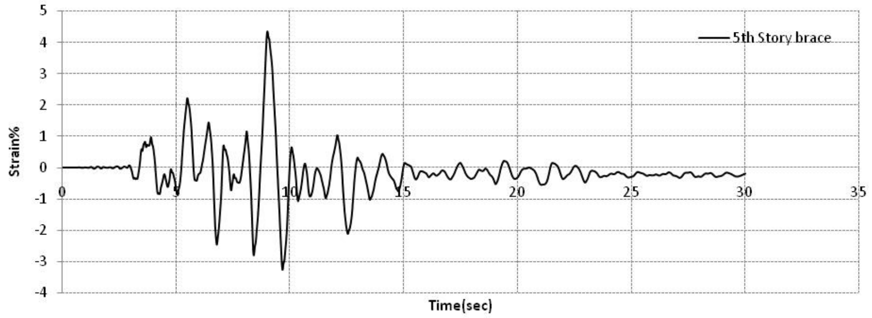

Figure 8: Strain history of fifth story brace in RL-BRBF under Northridge record.

The strain history of Northridge shows that the maximum strain amplitude is grater that 4%, but it only happens one time during the whole earthquake. Also the number of cycles in this strain history is low (the duration of earthquake is 30 seconds). In other words, although there are high strain amplitudes in strain history, but the number of these cycles is low. So, neither Imperial Valley nor Northridge record has a high damage index.

The clear difference between the damage indexes of designing and analysis is due to two possibilities. The selected records are not enough to give a general conclusion or AISC loading protocol does not include the LCF effects. It seems that AISC 341-05 does not represent a distinct criterion to control LCF failure in BRBs (especially RL-BRBs); while selecting a very short length can result in LCF failure. This topic could be a subject of research in future studies.

Finally it can be mentioned that, considering the sensitivity of LCF effects in RL-BRBs and the advantages of reducing yielding length in BRBs, there is an open space for the available seismic design codes to present some specific provisions regarding this issue.

For each brace, the mean value of maximum ductility demands from applied records were calculated and presented in Table 10. As expected the ductility demands in yielding length of RL-BRBs were much greater than the steel tips BRBs because a shorter yielding length is used. Previous studies confirm the high ductility values for BRBs with reduced yielding length [7].

Story	**Steel Tips**		**Reduce Length**	
	BF-1	BF-2	BF-1	BF-2
7	3	4	11	11
6	5	4	16	12
5	6	4	19	18
4	6	5	19	20
3	6	6	20	22
2	5	6	19	21
1	3	4	13	15

Table 10: The maximum ductility in yielding length of BRBs.

6 CONCLUSIONS

In present paper, different LCF studies on BRBs were presented and the suggested equations to estimate fatigue life of BRBs were mentioned. Using these equations and based on the rules of LCF damage estimation, a criterion was developed to determine the minimum of yielding length of the core in BRBs. This criterion was a single step of a step by step design procedure for RL-BRBFs. In order to evaluate the fatigue properties of the BRB with minimum yielding length through a time history analysis, a benchmark 7 story BRBF building was redesigned using RL-BRBs and it was tried to use the minimum possible yielding length. Then nonlinear dynamic analyses were conducted on both original and redesigned buildings. 28 analyses showed that reducing the yielding length of BRB increases the ductility demands on this part. Also the results of this damage index showed that in spite of high ductility demands, LCF effects are not critical and there is enough safety factor for LCF failure prevention. The maximum ductility of 11 to 22 (times of deformation at first yielding) and the cumulative inelastic ductility of 187 to 368 (times of deformation at first yielding) were imposed to the yielding length. The results of present study are valid for the selected records and can be extended for similar earthquakes with scientific judgments.

Key points were presented to reduce the risk of LCF failure for the BRBs. For future researches it is recommended to consider other records including artificial ones. Moreover developing a global loading protocol with enough safety factor for evaluating the LCF effects of BRBs is recommended for further researches.

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